Corrosion behavior of dental alloys used for retention elements in prosthodontics

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Corrosion behavior of dental alloys used for retention elements in prosthodontics

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Abstract

The purpose of this study was to investigate the corrosional behavior of ten different high noble gold-based dental alloys used for prosthodontic retention elements according to ISO 10271. Samples of ten high-noble and noble gold-based dental alloys were subjected to (a) static immersion tests with subsequent analysis of ion-release for eight different elements using mass spectrometry, (b) electrochemical tests including open-circuit potential and potentiodynamic scans, and (c) scanning electron microscopy, followed by energy-dispersive X-ray microscopy. The results were analyzed with one-way ANOVA and Sidak multiple comparisons *post hoc* test at $\alpha = 0.05$ level of significance. Significant differences were found among the ten alloys studied for all ions ($P<0.001$). The potentiodynamic analysis showed values from -82.5 to 102.8 mV for the open-circuit potential and from 566.7 to 1367.5 mV for the breakdown potential. Both the open-circuit and the breakdown potential varied considerably among these alloys. SEM analysis confirmed the existence of typically small-diameter corrosion defects, while the energy-dispersive X-ray analysis found no significant alteration in the element composition of the alloys. The results of this study reveal the variability in the corrosive resistance among the materials used for retention elements in prosthodontics.

Introduction

Corrosion of alloys occurs when elements in the alloy ionize and depends on a variety of factors like combination of 2 or more different alloys or the presence of pits or crevices (1, 2). The corrosion behavior of metallic materials usually is the most important property of a casting alloy concerning its biocompatibility, as release of metal ions is necessary for the development of biologic adverse effects (3).

Intraoral materials are subject to electrochemical reactions, mechanical forces of mastication, and generalized wear (4), which inevitably leads to their corrosion. Corrosion (or tarnish) of a metal alloy depends on many factors, including the alloy's composition and microstructure, mode of casting, and polishing, as well the characteristics of solutions used for alloy conditioning (5). It has also been documented that metal particles released from intraoral corrosion can penetrate plaque, gingival tissues and dental hard tissues (6–8). Intra-oral corrosion of dental alloys may lead to deterioration of the material and its properties and to a change of its biological compatibility (9), which in turn may result in pathological changes like gingival swelling, erythema and lichenoid reactions (10–12). Several metals and their intraoral corrosion products have been classified as carcinogenic, hazardous and priority toxic pollutants (13–16). Furthermore, since cytotoxicity is dose dependent (17), the intraoral accumulation of metal ions within a crevice is more likely to invoke adverse tissue reactions.

Many different types of alloys are used for prosthodontics, including a number of metals like gold, palladium, silver, nickel, cobalt, and titanium. High-noble alloys are known to be more resistant to corrosion than noble alloys, with gold being the most commonly used metal because of its high resistance to tarnish and corrosion (18). Interestingly however, most local adverse effects, such as the "burning mouth syndrome", were observed when noble and base alloys were combined (19). Many studies tested the in vitro corrosion characteristics of different commercial or experimental alloys, some (20) of which studied at the same time the electrochemical corrosion and ion release. However, as the variety of different dental alloys on the market is enormous, it is important to test them with respect to their corrosion behavior. Therefore, aim of this *in vitro* study was to evaluate the corrosion resistance for selected dental alloys. The null hypothesis was that there is no difference in the breakdown potential among the different alloys selected.

Materials and Method

Alloys

Alloys to be assessed in this investigation (Table 1) were selected according to the following inclusion criteria: (i) Type IV extra hard according to the DIN EN ISO1562, (ii) Vicker's hardness > 200 MPa, (iii) high ductility

(yield strength at 0.2 % elongation > 500 MPa), (iv) high modulus of elasticity (E > 80 GPa), and (v) avoidance of galvanic corrosion among different alloys. Although no galvanic corrosion was possible in the experimental setup of this study, choice of alloy was based on clinical relevance, where the intraoral potential for galvanic corrosion cannot be ruled out. Ten different alloys were used in this study that fulfilled all or almost all of these criteria. Their element composition and physical properties can be seen in Table 2 and Table 3, respectively. According to the American Dental Association's classification and their constituents (21), they could all be considered as high noble alloys (gold and platinum group ≥ 60%), except from a single noble alloy (gold and platinum group ≥ 25% - AL).

Electrolytes

In order to enable comparability with previous studies (22, 23), the used electrolyte was modified Fusayama solution (24) according to Geis-Gerstorfer and Weber (25) with a pH of 4.8.

Static immersion test and mass spectrometric analysis

For the static immersion test, six rectangular specimens (thickness 0.08 cm, edge length 1.25 cm, surface area 3.5 cm^2) from each alloy were used. All samples were cast and polished with 1200 SIC grit paper according to the requirements of ISO 10271 (9). Additionally, all bonding alloys were oxidized before polishing. All samples were cleaned ultrasonically for two minutes with ethanol. Each specimen was immersed in 3.5 ml of the test solution at a temperature of 37° C and maintained for a week. The concentrations of ions released were measured with Inductively Coupled Plasma Mass Spectrometry (ICP-MS, SCIEX ELAN 5000; Perkin Elmer, Waltham, MA, USA) for ions of the following elements: Au, Ir, Zn, Fe, Cu, Rh, In and Ta. Each specimen was analyzed three times and expressed as mean and Standard Deviation (SD). Weighted means were used to calculate a mean ion release for each ion type.

Electrochemical analysis

The electrochemical analysis was also conducted according to the requirements of ISO 10271 (9) with the same test solution as for the immersion test. Four rectangular samples (thickness 0.08 cm, edge length 0.35 cm, surface area 0.36 cm^2) of each alloy were used for the electrochemical test. The open circuit potential was measured for 2 hours. Subsequently the potential scan was started 150 mV below the open circuit potential and stopped after a current of 10 mA was reached. A potentiometer (Mlab200, Bank, Germany), an electrochemical

cell with a silver/silver-chlorine electrode as a reference electrode and a platinum electrode as a counter electrode were used to test the alloys. Connection of the sample to the circuit was realized via a titanium molybdenum wire cast into each sample. The surface of the wire was covered with silicone for insulation.

Scanning electron microscope (SEM) analysis

SEM images were taken with magnifications of 100, 1000 and 4000 after the static immersion testing and the electrochemical analysis with a XL-30 SEM (Philips Electron Optics, Eindhoven, The Netherlands). In order to differentiate between manufactural surface alterations and corrosive surface alterations, images were acquired from specimens both before and after the static immersion testing. SEM images were also acquired after the electrochemical analysis and compared to the images taken before the static immersion testing.

Energy dispersive X-ray microanalysis (EDX)

Additionally, in order to identify deposits or material alterations during the abovementioned tests, the elemental composition was identified by energy dispersive X-ray microanalysis (EDX), employing a spectrometer equipped with a super-ultrathin Be window Si(Li)detector (Sapphire, EDAX, Mahwah, NJ, USA) attached to the SEM. Spectra were collected at an area scan mode under 20 kV accelerating voltage, 98 μA beam current, 130 μm×130 μm collecting window, 500 s acquisition time, and 30~35 % dead time. The quantitative analysis was carried out by the Genesis software (version 2.5, EDAX) employing a nonstandard analysis and ZAF correction methods. The results for each element were averaged. The excitation depth was estimated as 1.8 μm.

Statistical analysis

Data normality was checked with the Kolmogorov-Smirnov test. As all data were normally-distributed, differences in the ion levels or electrochemical results among alloys were assessed with one-way ANOVA in Stata version 10 (StataCorp LP, College Station, Texas, USA). A possible association between the electrochemical results and the released ion levels was assessed descriptively. All alloys were ordered after increasing breakdown potential for all figures, as it was the most clinically relevant and showed the greater association with the results of the static immersion tests.

Results

Mass spectrometric results

The identified values of metallic ions released in the test solution within the observation week are given in Table 4. For the elements Ir, Ta and Rh the measured ion levels were below the ICP-MS detection limit of 0.1µg/l and therefore are not presented in Table 4. It is important to note that Au ions were released from all included alloys. The main ions with cytotoxic potential are the Zn and the Cu ions. The Zn ion release ranged from 0.09 to 17.62 µg/cm^2 with the lowest release being found for DH (0.09 µg/cm^2), followed by NC (0.30 µg/cm^2), and BM (0.32 µg/cm^2). The Cu ion release ranged from 0.00 to 0.61 µg/cm^2 with the lowest release being found for AL, BP, and DL, where the released ions were below the detection limit. The statistical analysis indicated that there were statistically significant differences among the alloys for almost all elements (Table S1).

Electrochemical results

As can be seen in Table 5, the open-circuit potential of the included alloys measured during two hours varied considerably, with mean values ranging between -82.5 to 102.8 mV, with significant differences identified with the ANOVA (Fig. 1; Table 5; Table S1). In total 12 of the 45 (27%) of the pairwise comparisons between alloys were significant (Tables S2)

The measured breakdown potential of all alloys according to ISO 10271 ranged between 558.3 to 1367.5 mV and was above the defined threshold of 550 mV (Fig 2; Table 5). It must be noted here, that the measurement for one out of the three specimens of the AL alloy was done on the linear and not the logarithmic scale, as no plateaus could be identified with the latter. The ANOVA testing indicated significant differences (Table S1), which were confirmed in 8 out of the 45 (18%) pairwise comparisons (Table S3). It must be noted here, however, that in all instances only the PM alloys varied significantly from the rest of the alloys, as it presented higher breakdown potential than the rest with the exception of EA (Fig. 2).

Associations between electrochemical and ion release results

The results of both electrochemical tests and static immersion tests in order of increasing breakdown potential can be seen in Fig. 3. As can be seen, no consistent agreement between the two experimental protocols could be seen, when the breakdown potential of the alloys was used as a reference. The only possible exceptions were the levels of ion release for Ag and Fe, where a possible association could be suspected. However, this trend was not unanimous across all elements releases and was not agree with the measured open-circuit potentials.

Scanning electron microscope results

Typical SEM pictures for the alloy Degunorm before and after the static immersion tests are shown in Fig 4. In general, after one week in the medium, no significant alteration of the alloy's surface could be seen. Typical SEM pictures before and after the forced electrochemical corrosion for the same alloy can be seen in Fig. 5. The corrosion defects were continuous, without interruptions from non-corroded areas with a typical diameter of 1000 µm. These should be viewed as typical examples of defects due to intraoral corrosion and not as before-and-after comparison of specific areas, as precise localization of the same areas was not possible.

EDX analysis

No considerable deposits on the alloy surfaces or alterations of the alloy compositions were found with the EDX analysis. However, during the static immersion analysis, ion leaching was identified that did not correspond to the manufacturer's specifications. For this reason, the element composition of each alloy was assessed with EDX and compared to the alloys' composition according to the manufacturer's specification (Table 6). Slight variation in the element composition was found in many instances. For example, the Au content in BP was lower than specified and in all other alloys higher as specified. On the other side, the Ag content was lower than specified for all alloys except EA. It must be noted however, that the accuracy of the EDX analysis is limited by the penetration depth of the electrons, which could explain these slight variations compared to the alloys' specifications. Therefore, no considerable differences between our measurements and the manufacturers' specifications can be supported, especially as no elements were traced that were not specified.

Discussion

A total of ten different high-noble and noble alloys used for prosthodontic retention elements were included and assessed in this study for their corrosion resistance. Comparisons with other studies are limited, due to different alloys being tested, experimental setups, and measurement procedures. The electrochemical analysis regarding both the open-circuit and breakdown potential of alloy PM agree with previous results (26).The results indicated that considerable differences were seen both in the amount of metal ions released and the results of the electrochemical analysis, with no apparent agreement between the results of the two procedures.

The measurement of corrosion is complex and, although many investigators have tried to predict corrosion of an alloy based on its composition, such predictions are difficult at best (27). Main ions leached from prosthodontic alloys with known cytotoxic properties are Zn and Cu released from gold alloys and Ni from base alloys (16). Leaching of Zn ions is expectable, as Zn is known by its lability and by the increase of its

release to double or triple from gold alloys after heat-treatment (28). Several studies have measured the corrosional release of Zn ions from noble or high-noble dental alloys (29-33), but comparisons with the present study are limited, due to differences in the alloys and the methodology. Additionally, Pd contained in dental casting alloys has been the subject of major controversies and concerns about possible adverse biological reactions, such as toxic and allergenic effects (34).

Several factors can influence the corrosion resistance of dental alloys, with the main being the alloy's element composition. Previous corrosion studies have reported that low- or no-gold alloys presented increased ion leaching compared to high-gold alloys (35, 36). High-noble and noble alloys are more resistant to corrosion than base metal alloys and therefore gold is commonly used, due to its high corrosion resistance (18). Also, the corrosion resistance of low-gold alloys is less than that of high-gold dental alloys (37). Additionally, the corrosion potential of Pd-based alloys has been shown to be high (38-42) and even higher than pure gold (26). Pd has also been reported to reduce the lability of gold dental alloys (3). It is interesting to note, that the corrosion-reducing effect of increases of the Pd %wt, seems to be greater than the corrosion-reducing effect of increases in the Au %wt (43). Additionally, multiple phases will often increase the elemental release from alloys (44). Most often single-phase alloys, the Au-Ag-Cu alloys generally have poorer corrosion properties than their high-noble counterparts if the copper or silver has been increased to more than 15 wt % (45). Furthermore, certain elements have an inherently higher tendency to be released from dental alloys, regardless of the alloy composition (44, 46). Third, certain environmental conditions around the alloy will affect the elemental release. For example, significantly stronger corrosion phenomena of high-noble alloys can be observed at a pH of 4, or even worse at a pH of 1, compared to a pH of 7, although these are more pronounced for base alloys (45, 47, 48). Wear is another important factor which can accelerate corrosive processes in vivo. The structure of the alloy, single- or multiple-phase, is also an important factor in its corrosion resistance (3). To a great extent however, the alloy structure depends on the alloying elements and their combinations and concentration in the alloy (3, 20, 28). On the other hand, some alloying elements are known by their lability more than other elements (3, 28) and some alloying combinations result in synergetic effects altering elements' lability and thus increasing or decreasing the corrosion rate (3, 28, 49).

Significant variations in the open-circuit potential of the assessed alloys were found, with DM and PM presenting the highest values. Generally speaking, a high open-circuit potential is associated with a high corrosion resistance of the alloy. This can be attributed to the tendency of an alloy to oxidate or to release soluble components, as in the example of Zn (3). Although measurements of the open-circuit potential were

made during 2 hours, according to the ISO 10271, Manaranche and Homberger (3) reported that the open-circuit potential reaches equilibrium after 24 hours. Furthermore, according to ISO 10271, the open-circuit potential was supplemented by the measurement of the breakdown potential of the alloys through forced corrosion, where EA and PM presented the highest values. It must be noted, that the breakdown potential reflects a forced and rapid corrosion procedure, which might not be so easily translated to the clinical reality. It has also been shown, that the open-circuit and breakdown potentials correlate only weekly (50). For this reason, it is advisable that the corrosion resistance of an alloy is tested comprehensively with a combination of these procedures to draw safe conclusions (51).

The SEM analyses are in agreement with the electrochemical results and indicate good corrosion resistance of all three alloy specimens in conditions simulating those in the oral cavity.

Exact replication of the conditions in the oral cavity is impossible in laboratory conditions, as many factors are difficult to control. For example, the pH of the saliva in the oral cavity is subject to individual as well as temporal changes, as it depends on a multiplicity of parameters (52). Additionally, the measurement of breakdown potentials follows a type of forced electrochemical corrosion. While this method does not simulate realistic intraoral corrosion conditions, it allows comparing the corrosion behavior of various dental alloys under standardized conditions. Furthermore, the comparison of the laboratory results with the intraoral situation is hardly possible, due to the fact that potentiostatic loads in the mouth are much smaller than under laboratory conditions. Also, although EDX analysis is mostly used for the qualitative rather than the quantitative analysis of light elements, the quantitative results are given here to indicate the differences in the composition of the used alloys. In so far, corrosion testing according to standard protocol seems to be an appropriate means to determine corrosion resistance of dental alloys. However, according to the results of the ICP-MS analysis, the average levels of released ions for many elements were below or close to the detection limit. Given the fact that this study was carried out according to the requirements of ISO 10271 (9), these results should be interpreted appropriately under the light of the specific characteristics of the methodological setup, its lack of agreement with the electrochemical tests, and its corresponding clinical relevance.

Summarizing, according to the results of the static immersion test and the electrochemical analyses, all tested alloys are sufficiently resistant to corrosion and suitable for clinical application, although significant differences exist among them. A substantial agreement between the results of the static immersion tests and the electrochemical tests could not be observed.

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Conflicts of interest – The authors have no conflicts of interest to declare.

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Figure legends

Fig. 1. Measured open-circuit potentials in mV for the alloys tested. Alloys are listed in order of increasing breakdown potential. The boxes and whiskers correspond to the interquartile ranges and ranges, respectively. The blue dotted horizontal lines correspond to medians.

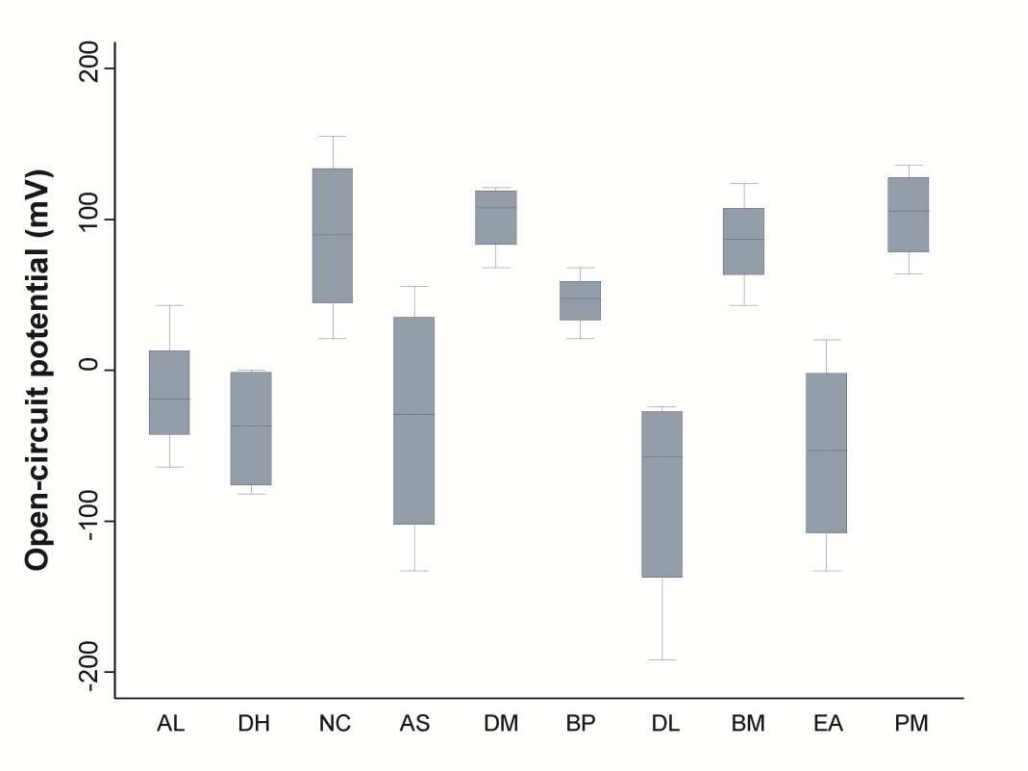

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Fig. 2. Measured breakdown potentials in mV for the alloys tested. Alloys are listed in order of increasing breakdown potential. The boxes and whiskers correspond to the interquartile ranges and ranges, respectively. The blue dotted horizontal lines correspond to medians.

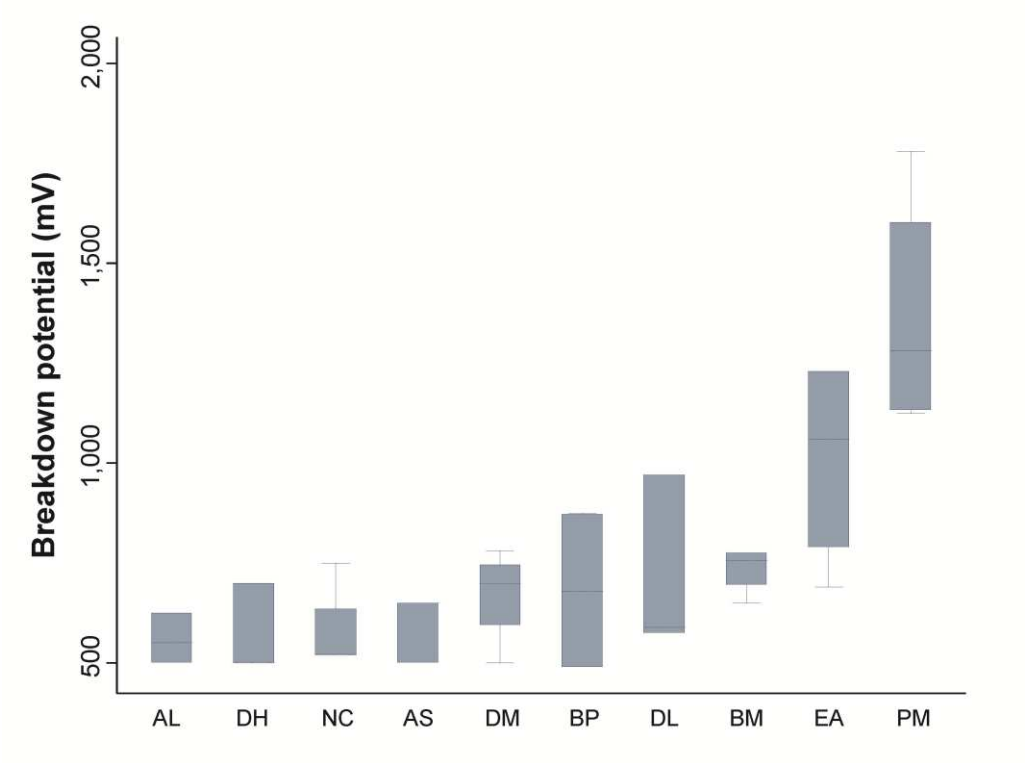

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Fig. 3. Graph of possible associations between electrochemical and static immersion results. Alloys are sorted according to increasing breakdown potential (not shown).

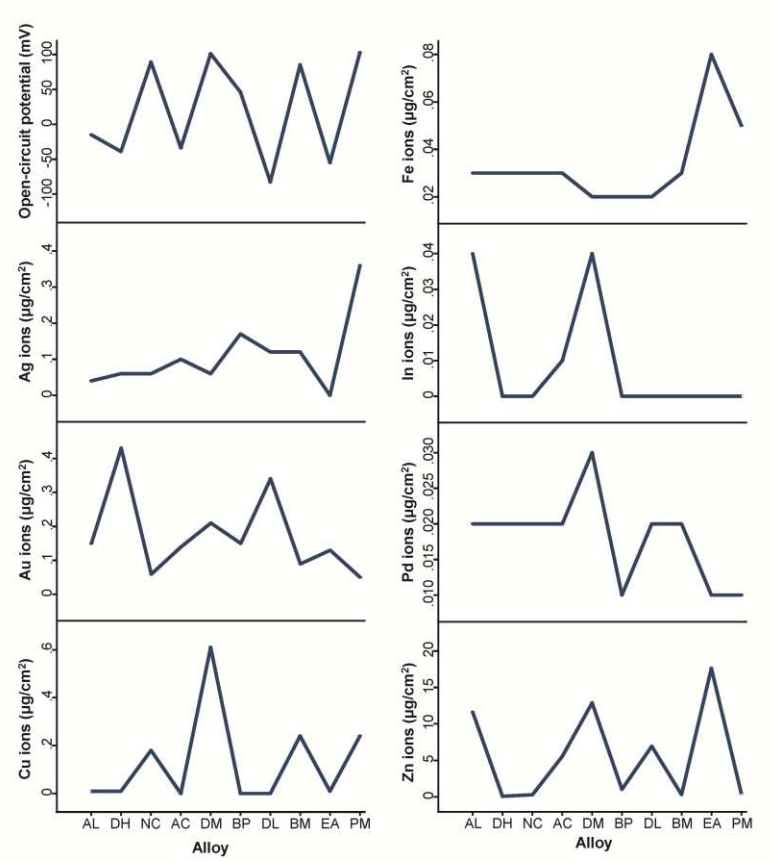

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Fig. 4. Typical SEM images of an alloy (Degunorm) (A) prior to and (B) after static immersion test corrosion at a magnification of 1000x.

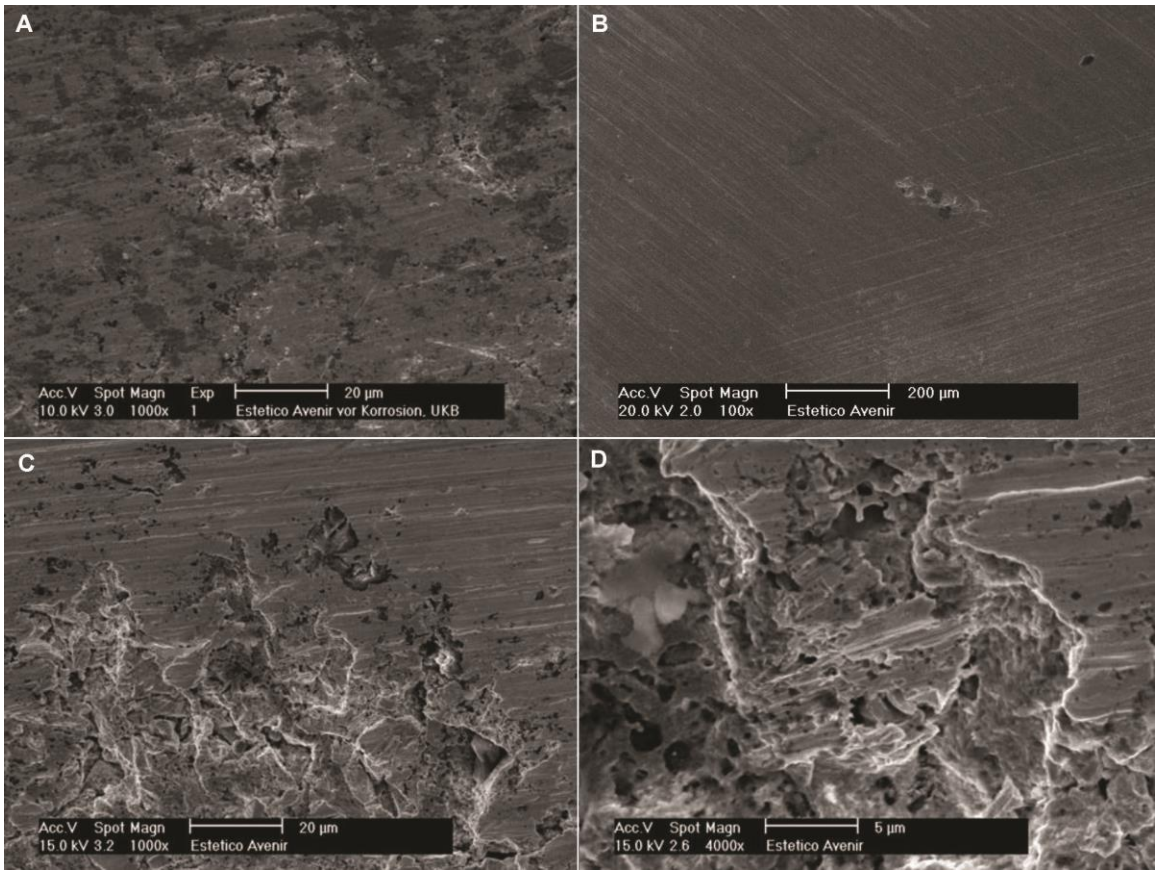

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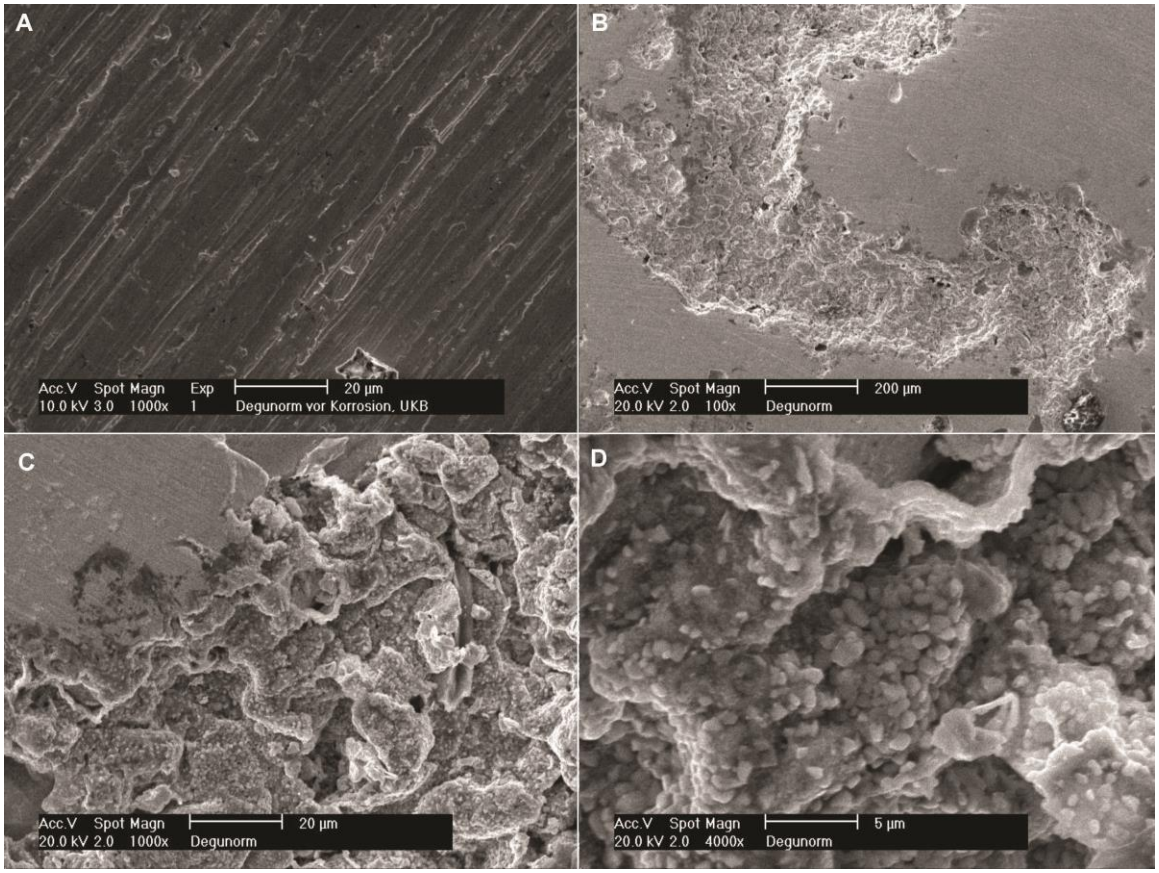
Fig. 5. Typical SEM images of samples from Degunorm prior to and after electrochemical corrosion test. (A) Degunorm before corrosion at magnification of 1000x, (B) Degunorm after corrosion at magnification of 100x, (C) Degunorm after corrosion at magnification of 1000x, and (D) Degunorm after corrosion at magnification of 4000x.



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TABLES

Table 1

List of the alloys used in this study, together with abbreviations

Manufacturer	Alloy	Abbreviation
Cendres + Métaux, Biel, Switzerland	Neocast III	NC
	Esteticor Avenir	EA
DeguDent, Hanau, Germany	Degudent H	DH
	Degunorm	DM
	Degudent LTG	DL
Metalor, Neuchatel, Switzerland	Pontor MPF	PM
Wieland, Pforzheim, Germany	Bio Portadur	BP
	AGC Special	AS
ZL Microdent, Breckerfeld, Germany	Allround 55 LF	AL
	Benchmark III	BM

Table 2

List of the alloys used in this study, together with their alloy composition in % weight. Alloys are listed alphabetically.

Aloy	%Au	%Pt	%Pd	%Ir	%Ag	%Zn	%Sn	%Fe	%Cu	%Rh	%In	%Ta
AL	55.90	-	8.50	0.10	31.00	1.60	-	-	-	0.10	2.80	-
AS	85.80	11.40	-	-	-	1.50	-	0.40	-	0.50	0.30	-
BM	74.00	4.00	-	0.01	10.70	0.58	-	-	10.70	-	-	-
BP	85.30	10.00	-	-	-	3.00	-	-	-	0.70	0.10	-
DH	84.40	8.00	5.00	-	-	-	-	-	-	-	2.50	0.10
DL	73.10	1.50	5.80	0.10	16.80	3.00	0.50	-	-	-	-	-
DM	73.80	9.00	-	0.10	9.20	2.00	-	-	4.40	-	1.50	-
EA	84.00	10.90	2.40	0.10	0.20	2.20	-	0.20	-	-	-	-
NC	71.60	3.75	-	0.05	12.70	1.10	-	-	10.80	-	-	-
PM	72.00	3.60	-	-	13.70	0.90	-	-	9.80	-	-	-

Table 3

Physical properties of the alloys used in this study based on the manufacturer's data. Alloys are listed alphabetically.

Alloy	Density (g/cm^3)	Preheating Temp. (°C)	Casting Temp. (°C)	Porcelain -fired?	HV 5 HA	HV 5 NG	E (GPa)
AL	13.9	760°	1250°	Yes	220	193	-
AS	18.8	800°	1250°	Yes	170	166	103
BM	15.8	700°	1090°	No	220	196	-
BP	18.2	700°	1220°	No	170	178	99
DH	18.1	850°	1400°	Yes	200	177	95
DL	15.7	750°	1210°	Yes	235	227	82
DM	16.7	700°	1200°	Yes	200	191	100
EA	18.7	800°	1290°	Yes	210	198	98
NC	15.5	680°	1000°	No	245	230	97
PM	15.6	680°	1160°	No	220	206	100

VH, Vickers Hardness.

Table 4

Ion releases as mean (standard deviation) in µg/cm² after immersion tests for the tested elements. Alloys are listed alphabetically.

	Ag	Au	Cu	Fe	In	Ir	Pd	Rh	Zn	Ta
Alloy	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)
AL	0.04 (ND)	0.15 (ND)	0.01 (ND)	0.03 (ND)	0.04 (ND)	nd (ND)	0.02 (ND)	nd (ND)	11.63 (0.03)	nd (ND)
AS	0.10 (0.03)	0.14 (0.01)	0.00 (ND)	0.03 (ND)	0.01 (ND)	nd (ND)	0.02 (ND)	nd (ND)	5.56 (0.01)	nd (ND)
BM	0.12 (0.02)	0.09 (ND)	0.24 (ND)	0.03 (ND)	nd (ND)	nd (ND)	0.02 (ND)	nd (ND)	0.32 (ND)	nd (ND)
BP	0.17 (0.02)	0.15 (ND)	0.00 (ND)	0.02 (ND)	nd (ND)	nd (ND)	0.01 (ND)	nd (ND)	1.04 (ND)	nd (ND)
DH	0.06 (0.02)	0.43 (0.01)	0.01 (ND)	0.03 (ND)	nd (ND)	nd (ND)	0.02 (ND)	nd (ND)	0.09 (ND)	nd (ND)
DL	0.12 (0.03)	0.34 (0.01)	0.00 (ND)	0.02 (ND)	nd (ND)	nd (ND)	0.02 (ND)	nd (ND)	6.94 (0.02)	nd (ND)
DM	0.06 (0.01)	0.21 (ND)	0.61 (ND)	0.02 (ND)	0.04 (ND)	nd (ND)	0.03 (ND)	nd (ND)	12.89 (0.03)	nd (ND)
EA	0.00 (ND)	0.13 (ND)	0.01 (ND)	0.08 (ND)	nd (ND)	nd (ND)	0.01 (ND)	nd (ND)	17.62 (0.03)	nd (ND)
NC	0.06 (ND)	0.06 (ND)	0.18 (ND)	0.03 (ND)	nd (ND)	nd (ND)	0.02 (ND)	nd (ND)	0.30 (ND)	nd (ND)
PM	0.36 (ND)	0.05 (ND)	0.24 (ND)	0.05 (ND)	nd (ND)	nd (ND)	0.01 (ND)	nd (ND)	0.42 (ND)	nd (ND)

SD, standard deviation; nd, mean ions released below the detection limit; ND, small variation among the six samples tested, leading to a standard deviation under the detection limit)

Table 5

Open-circuit and breakdown potential of the analyzed alloys in mV. Alloys are listed alphabetically.

Alloy	Open-circuit potential Mean (SD)	Breakdown potential Mean (SD)
AL	-15.0 (44.0)	558.3 (62.9)
AS	-33.8 (85.0)	600.0 (86.6)
BM	85.3 (33.3)	735.0 (59.0)
BP	46.0 (19.4)	681.3 (220.9)
DH	-39.0 (43.6)	566.7 (115.5)
DL	-82.5 (77.6)	711.7 (223.9)
DM	101.0 (24.2)	670.0 (119.7)
EA	-55.0 (67.0)	1010.0 (266.8)
NC	89.0 (57.6)	577.5 (115.0)
PM	102.8 (31.6)	1367.5 (307.7)

SD, standard deviation.

Table 6

Comparison of the element composition (weight %) found from the EDX analysis compared to the manufacturers' specificactions. Positive values correspond to higher element content compared to the manufacturers' specifications. Alloys are listed alphabetically.

Alloy	%Au	%Pt	%Pd	%Ir	%Ag	%Zn	%Sn	%Fe	%Cu	%Rh	%In	%Ta
AL	+3.9	-	-1.2	*	-1.4	*	-	-	-	*	+0.5	-
AS	+6.9	-5.0	-	-	-	*	-	*	-	*	+0.6	-
BM	+0.9	+1.0	-	+0.7	-1.8	-0.1	-	-	-0.7	-	-	-
BP	-4.4	+4.5	-	-	-	-0.4	-	-	-	+0.1	+1.1	-
DH	+4.5	-2.4	-0.8	-	-	-	-	-	-	-	-1.1	*
DL	+4.8	+1.5	-1.5	*	-3.2	-2.1	-0.1	-	-	-	-	-
DM	+1.1	-2.9	-	*	-1.0	+0.6	-	-	+3.8	-	*	-
EA	+3.6	-2.0	+0.1	*	+0.6	-2.0	-	*	-	-	-	-
NC	+4.2	-1.0	-	*	-1.7	-0.8	-	-	0.0	-	-	-
PM	+3.0	+0.0	-	-	-1.9	-0.5	-	-	-0.6	-	-	-

*No element traces were found from the EDX analysis for this element, although this element exists according to the manufacturer's specifications.

Corrosion behavior of dental alloys used for retention elements in prosthodontics

Supporting Information

Table S1
Analysis of variance for differences among the alloys used

Factor	Sum of squares	df	Mean square	F statistic	P-value
Ag ions	0.562	9	0.062	197.31	<0.001
Au ions	0.787	9	0.087	2503.12	<0.001
Cu ions	2.095	9	0.233	180000	<0.001
Fe ions	0.019	9	0.002	1981.69	<0.001
In ions	0.012	9	0.001	3710.03	<0.001
Ir ions	0.000	9	0.000	1.21	0.311
Pd ions	0.003	9	0.000	248.73	<0.001
Rh ions	0.000	9	0.000	2.00	0.0589
Zn ions	2218.86	9	246.54	810000	<0.001
Ta ions	0.000	9	0.000	$5.1*10^{32}$	<0.001
Open-circuit potential	187317.13	9	20813.01	7.45	<0.001
Breakdown potential	2236738.89	9	248526.54	7.29	<0.001

df, degrees of freedom.

Table S2

P-values for post hoc pairwise comparisons regarding the open-circuit potential of the various alloys

Alloy	AL	AS	BM	BP	DH	DL	DM	EA	NC	PM
AL										
AS	1.00									
BM	0.41	0.14								
BP	1.00	0.85	1.00							
DH	1.00	1.00	0.10	0.75						
DL	0.98	1.00	**0.004**	0.08	1.00					
DM	0.17	**0.059**	1.00	1.00	**0.034**	**0.001**				
EA	1.00	1.00	**0.033**	0.40	1.00	1.00	**0.011**			
NC	0.34	0.11	1.00	1.00	0.08	**0.003**	1.00	**0.025**		
PM	0.15	**0.043**	1.00	1.00	**0.030**	**0.001**	1.00	**0.009**	1.00	

Bold values indicate statistical significance at the 5% level.

Table S3

P-values for post hoc pairwise comparisons regarding the breakdown potential of the various alloys

Alloy	AL	AS	BM	BP	DH	DL	DM	EA	NC	PM
AL										
AS	1.00									
BM	1.00	1.00								
BP	1.00	1.00	1.00							
DH	1.00	1.00	1.00	1.00						
DL	1.00	1.00	1.00	1.00	1.00					
DM	1.00	1.00	1.00	1.00	1.00	1.00				
EA	0.15	0.28	0.87	0.57	0.17	0.87	0.50			
NC	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.12		
PM	**<0.001**	**<0.001**	**0.002**	**0.001**	**<0.001**	**0.004**	**0.001**	0.39	**<0.001**	

Bold values indicate statistical significance at the 5% level.